Naval Surface Warfare Center
Carderock Division
West Bethesda, MD 20817-5700

NSWCCD-61-TR–2004/11 **July 2004**

Survivability, Structures, and Materials Department

Technical Report

Fatigue Crack Growth Rate Behavior in Titanium Alloy Ti-5111 Weld Metal

by

Amy C. Stauffer and Ernest J. Czyryca

NSWCCD-61-TR–2004/11 Fatigue Crack Growth Rate Behavior in Titanium Alloy Ti-5111 Weld Metal

Naval Surface Warfare Center
Carderock Division
West Bethesda, MD 20817-5700

NSWCCD-61-TR–2004/11 **July 2004**

Survivability, Structures, and Materials Department
Technical Report

Fatigue Crack Growth Rate Behavior in Titanium Alloy Ti-5111 Weld Metal

by
Amy C. Stauffer and Ernest J. Czyryca

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

REPORT DATE (DD-MM-YYYY)
06 2004

2. REPORT TYPE
FINAL

3. DATES COVERED (From - To)

4. TITLE AND SUBTITLE

Fatigue Crack Growth Rate Behavior in Titanium Alloy Ti-5111 Weld Metal

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Amy C. Stauffer, Ernest J. Czyryca (NSWCCD)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AND ADDRESS(ES)

NAVAL SURFACE WARFARE CENTER
CARDEROCK DIVISION (CODE 614)
9500 MACARTHUR BLVD
WEST BETHESDA MD 20817-5700

8. PERFORMING ORGANIZATION REPORT NUMBER

NSWCCD-61-TR–2004/11

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

CHIEF OF NAVA RESEARCH
ATTN ONR-332
BALLSTON CENTRE TOWER ONE
800 N QUINCY STREET
ARLINGTON VA 22217-5660

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Fatigue crack growth rate (FCGR) tests were conducted on Titanium Alloy Ti-5111 weld metal in air, artificial seawater, and artificial seawater with an applied cathodic potential. The results indicated a minor effect of seawater in increasing FCGR of Ti-5111 weld metal. However, the application of a cathodic potential of 0.987 V versus Ag/AgCl reference electrode showed crack growth rates similar to FCGR in air. Additionally, comparisons are made regarding the FCGR behavior of Ti-5111 plate, Ti-100 (Ti-621-0.8Mo) plate, and Ti-5111 weld metal in both air and seawater. These results indicated that both high strength titanium alloy grades, including the base and weld metal, performed similarly in all test environments.

15. SUBJECT TERMS

Titanium Alloy Ti-5111 Fatigue crack growth rate FCGR

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Amy C. Stauffer
a. REPORT UNCLASSIFIED	b. ABSTRACT UNCLASSIFIED	c. THIS PAGE UNCLASSIFIED	SAR	30	19b. TELEPHONE NUMBER *(include area code)* 301-227-5008

Standard Form 298 (Rev. 8-98)

Prescribed by ANSI Std. Z39.18

CONTENTS

FIGURES

TABLES

ADMINISTRATIVE INFORMATION

The work described in this report was performed by the Metals Division (Code 61) of the Survivability, Structures and Materials Department at the Carderock Division, Naval Surface Warfare Center. The work was funded by the Naval Sea Systems Command, Metals and Welding Division (SEA 05M2) as part of the Metallic Material Advanced Development and Certification Program (Program Element 0603573N). The Technical Agent for the work was Mr. Gene Mitchell (SEA 05M2).

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the assistance and instruction provided by Dr. Richard E. Link, USNA, in enabling this investigation, and the contribution of Dr. Peter S. Pao of the Naval Research Laboratory of previously unpublished fatigue crack growth studies on titanium alloy Ti-5111.

This page intentionally left blank

EXECUTIVE SUMMARY

Fatigue crack growth rate (FCGR) tests were conducted on titanium alloy Ti-5111 weld metal in air, artificial seawater, and artificial seawater with an applied cathodic potential. The results indicated a minor effect of seawater in increasing FCGR of Ti-5111 weld metal. However, the application of a cathodic potential of 0.987 V versus Ag/AgCl reference electrode showed crack growth rates similar to FCGR in air. Additionally, comparisons are made regarding the FCGR behavior of Ti-5111 plate, Ti-100 (Ti-621-0.8Mo) plate, and Ti-5111 weld metal in both air and seawater. These results indicated that both high strength titanium alloy grades, including the base and weld metal, performed similarly in all test environments.

INTRODUCTION

The fatigue crack growth rate behavior in high strength alloys is required for structural integrity assessments of structures that undergo cyclic loading in service. Such information is especially important for flaw growth analyses of welds, where non-destructive examination may indicate defects, and repair or fitness-for-service decisions must be supported. This report describes fatigue crack growth rates (FCGR) in titanium alloy Ti-5111 (Ti-5Al-1Sn-1Zr-1V-0.8Mo) weld metal in air and in synthetic seawater. The results are compared to those of Ti-5111 and Ti-100 (Ti-6Al-2Cb-1Ta-0.8Mo) plate.

Ti-5111 is a near-alpha titanium alloy developed jointly by the Navy and Titanium Metals Corporation (TIMET) for intermediate strength, high toughness, good weldability, stress-corrosion cracking resistance, and room temperature creep resistance. The Ti-5111 alloy was developed to have properties equal to titanium alloy Ti-100, but capable of being produced at lower cost with greater product yield than Ti-100 [1, 2, 3, 4]. Titanium alloys vary in their sensitivity to corrosion fatigue in the marine environment. Therefore, this investigation focused on the determination of the effects of seawater and applied cathodic potential on fatigue crack propagation in Ti-5111 plate and weld metal. Prior FCGR studies by the Naval Research Laboratory [5] and TIMET [2] established fatigue crack growth rates in Ti-5111 plate in air and seawater and provided a basis of comparison of base metal properties with this evaluation of Ti-5111 weld metal FCGR. The effects of applied cathodic potential on the fatigue crack growth behavior of the Ti-5111 weld metal were determined. Finally, data from studies on Ti-100 fatigue crack propagation [6] were used to directly compare fatigue crack growth behavior in the two titanium alloys.

MATERIALS INVESTIGATED

All weld metal (AWM) fatigue crack growth rate (FCGR) specimens were machined from two 1-inch thick weldments of Ti-5111 plate (TIMET Heat #T-6253, ASTM B 265, Grade 32). The weldments identification codes were HGC and HGF. The plate was produced from part of a 4500kg ingot that was triple melted, forged into a slab, and subsequently beta-rolled into plates and alpha/beta annealed. Two separate weldments were produced under the conditions outlined in Table 1. The filler metal used for both welds was matching Ti-5111 weld wire, 0.062 and 0.165-inch diameter, drawn from TIMET Heat #6253. Both weldments were in the as-welded condition.

Table 1: Weld Conditions for Ti-5111 Fatigue Crack Growth Rate Specimens

Welding Facility	Carderock Division	Titanium Fabrication
Weld ID	HGC	HGF
Process Mode	Automatic	Manual
Joint Design	Double bevel (K-joint)	Single-V, 60°
Condition	As-welded	Stress Relieved

The chemical compositions of the Ti-5111 plate, filler wire, and the as-deposited weld metal are shown in Table 2. The plate composition was within the limits specified by ASTM B 265, Grade 32, and the filler wire and deposited weld metal compositions were within the limits specified by AWS A5.16, Grade 32; including the levels of interstitial hydrogen (0.0050 max.), oxygen (0.08 max.), and carbon (0.03 max.).

Table 2: Chemical Composition of Ti-5111 Plate,
Weld, and Filler Wire (weight %)

Element	B 265 Grade 32	Parent Plate	Weld Wire	Weld Metal
Aluminum	4.5-5.5	5.30	5.18	5.26
Tin	0.6-1.4	1.11	1.06	1.03
Vanadium	0.6-1.4	1.12	1.07	1.00
Zirconium	0.6-1.4	1.07	1.08	0.96
Molybdenum	0.6-1.2	0.82	0.79	0.75
Iron	0.25 max	0.099	0.034	0.055
Silicon	0.06-0.14	0.13	0.12	0.09
Oxygen	0.11 max	0.087	0.047	0.053
Carbon	0.08 max	0.005	0.008	0.008
Nitrogen	0.03 max	0.005	0.005	0.004
Hydrogen	0.015 max	0.0100	0.0022	0.0030

Cross-sections of the weldments were polished and etched for macro graphic examination. Photo macrographs of the transverse cross-section of the double-bevel K joint weld, HGC, and the single-V weld are shown in Figures 1 and 2, respectively. Visual examination of both welds determined the weld metal to be sound, with no indications of cracks, porosity, or defects. Hardness testing was conducted across the weld metal, heat-affected zones,

and base metal. The hardness across each region was consistent and ranged from 28 to 32 HRC for the weld metal and HAZ and from 27 to 30 HRC for the base plate.

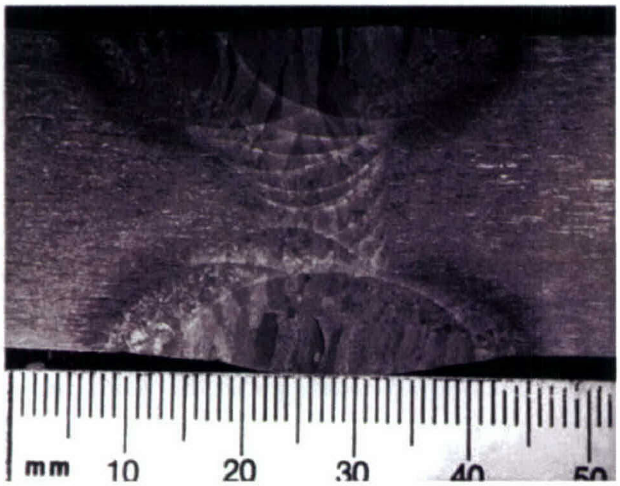

Figure 1: Macrograph of Ti-5111 Double-bevel GTAW K-Joint, Code HGC

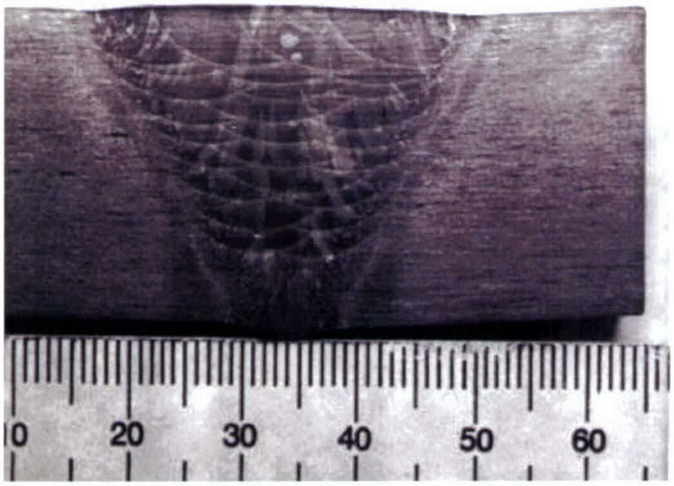

Figure 2: Macrograph of Ti-5111 Single-V GTAW Joint, Code HGF

MECHANICAL PROPERTIES

Mechanical property testing of the Ti-5111 plate and weld metal was conducted [4]. Tensile tests (ASTM E 8) of the Ti-5111 plate and all weld metal were conducted using standard 0.505-inch diameter specimens. Charpy V-notch (ASTM E 23) and 5/8-inch dynamic tear (ASTM E 604) impact toughness tests were conducted on the plate and weld metal. In the weld metal toughness tests, the specimens were notched to fracture in the welding direction. The Charpy V-notch and dynamic tear tests were all conducted at 30 °F. A summary of the results for welds HGC and HGF, and the Ti-5111 parent plate are provided in Table 3. The Ti-5111 parent plate and weld metals met or exceeded the minimum tensile properties of ASTM B 265, Grade 32, and both weld metals exceeded the interim minimum toughness requirements for Navy applications based on Ti-100 weld metal.

Table 3: Mechanical Properties of Ti-5111 Weld Metal and Parent Plate.

Material	Ultimate Tensile Strength (ksi)	0.2% Yield Strength (ksi)	Elongation (%)	Reduction of Area (%)	Charpy V-notch Impact Energy (ft-lbs)	5/8-inch Dynamic Tear Energy (ft-lbs)
Ti-5111 Plate (T-6253) 1-inch Thick (L-T)	122.7 123.0	104.3 105.5	14 11.5	25.5 31.0	35, 32, 37, 35	402, 382
Automatic GTAW Code HGC	135.6	128.6	12	31	34, 36, 38, 34, 38, 38	270, 280
Manual GTAW Code HGF	127.0 126.7	112.3 114.0	9 9	24 21	48, 41, 43, 42, 47, 43	270, 330
ASTM B 265, Grade 32 for Plate (minimum)	100	85	10	*	*	*
Interim Ti-5111 Weld Metal Toughness (minimum)	-	-	-	-	25	200

Note: *=not specified.

EXPERIMENTAL PROCEDURE

The fatigue crack growth rate tests were performed on five all-weld-metal (AWM) compact tension specimens, a schematic (adapted from ASTM E 647) of the compact tension type specimen, C(T), is shown in Figure 3. The specimens were machined with the notch in the welding direction (T-L), approximately in the center of the weld metal. The FCGR tests were conducted in accordance with ASTM Standard Test Method E 647 for Measurement of Fatigue Crack Growth Rates.

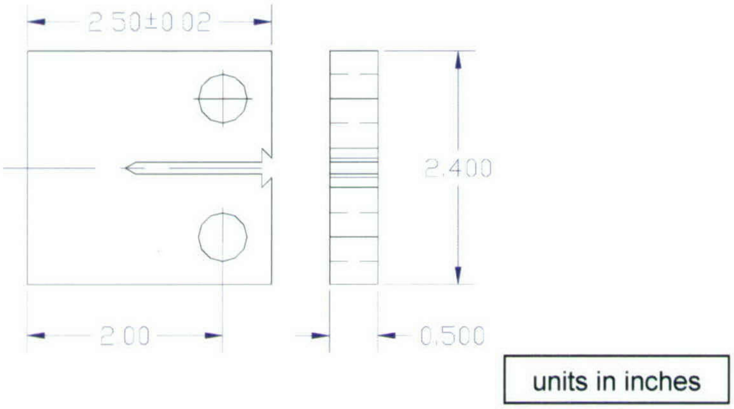

Figure 3: Schematic of the Compact Tension Specimen Used in Fatigue Crack Growth Rate Tests

The FCGR tests were performed using a 10,000 lb servo-hydraulic, closed-loop testing system with computer-assisted control and data collection. The tests were conducted under constant load amplitude, using a sine-wave function. Crack length (a) was estimated from specimen compliance (α) using the following expression:

$$a = W\,(1.001 - 4.6695\alpha + 18.46\alpha^2 - 236.82\alpha^3 + 1214.9\alpha^4 - 2143.6\alpha^5) \qquad (1)$$

where

$$\alpha = \frac{1}{\left(\frac{E' vB}{P}\right)^{1/2} + 1} \qquad (2)$$

and

E′ = effective modulus of elasticity ≈ 16 X 10^6 psi
B = specimen thickness, inch
v = crack opening displacement, inch
P = load, lb

The effective modulus of elasticity accounts for any differences between the physical and compliance crack size measurements and uncertainty in the actual value of the elastic modulus. The value of E′ must be within 10% of the typical elastic modulus for the results to be valid.

Tests were typically conducted from a crack-tip intensity factor range (ΔK) of 15 ksi√in to 50 ksi√in (see Table 4 for exact values). The crack-tip intensity of each data point is given by Equation (3), as follows:

$$\Delta K = \frac{\Delta P}{BW^{\frac{1}{2}}} * \frac{\left(2 + a/W\right)}{\left(1 - a/W\right)^{\frac{3}{2}}} * f\left(a/W\right) \tag{3}$$

where

W = specimen width, inch

a/W = normalized crack size

ΔP = load range, lb

and

$$f\left(a/w\right) = 0.866 + 4.64\left(a/w\right) - 13.32\left(a/w\right)^2 + 14.72(a/w)^3 - 5.6\left(a/w\right)^4 \tag{4}$$

The specimens were pre-cracked in air at a frequency of 20 Hz and a load ratio of $R = P_{max}/P_{min} = 0.1$

The FCGR tests were conducted at ambient laboratory temperatures in air, standard aerated artificial seawater (ASTM D 1141), and aerated artificial seawater with an applied cathodic potential. The crack front was submerged in the seawater with fresh seawater dripping continuously into a containment cell surrounding the crack. An Ag/AgCl reference electrode and a graphite counter electrode were used to apply a constant cathodic potential of 0.987 V in tests with applied potential to simulate the presence of a zinc anode in proximity. The FCGR test parameters are summarized in Table 4. Specimens tested in seawater were tested at a lower frequency to allow time for potential corrosion to occur.

Table 4: Test Parameters for Ti-5111 Weld Metal FCGR Tests.

C(T) Specimen No.	Frequency (Hz)	Load Ratio R	Test Environment	Range of ΔK in Test	
				Lowest ΔK (ksi√in)	Highest ΔK (ksi√in)
HGC-11	5	0.1	air	8	40
HGC-8	1	0.1	sw	10.8	50
HGF-7A	1	0.1	sw w/cp	15	50
HGF-7B	1	0.1	sw	15	50
HCG-13	1	0.1	sw w/cp	15	50

Notes:

Sw =artificial seawater;
sw w/cp = seawater with applied cathodic potential.

RESULTS AND DISCUSSION

The fatigue crack growth data are presented on typical fatigue crack growth rate plots, where the change in crack growth per cycle (da/dN) is plotted versus the crack-tip stress intensity factor range (ΔK) on a logarithmic plot. Typically, these plots display three distinct regions with an overall sigmoid shape [7]. Region I is the region of slow crack growth characterized by the stress intensity threshold value (ΔK_{th}), below which cracks do not grow. Region II is termed the "Paris" regime because the crack growth behavior is follows the Paris Law:

$$da/dN = C(\Delta K)^n \tag{5}$$

where C = Paris coefficient and n = crack growth exponent.

This region is often linear in log-log plot, allowing one to calculate the crack growth rate behavior of a material until it reaches region III. In region III, cracks approach a critical stress intensity value, where unstable crack growth leads to fracture.

The focus of these tests was to obtain FCGR data within the Paris Law regime, while obtaining K_{th} and K_{crit} data was outside the scope. Fatigue crack growth rate behavior of Ti-5111 weld metal in air is shown in Figure 4. A power-law trend line was added to the plot to obtain the Paris coefficient and crack growth exponent, where:

$$C = 4.25e^{-11} \frac{in/_{cycle}}{ksi\sqrt{in}}$$

and n = 3.87.

These results were used as a baseline for comparison to FCGR data of Ti-5111 weld metal in seawater and seawater with applied cathodic potential, as well as comparison to Ti-5111 FCGR data for plate and FCGR data for Ti-100 alloy. The variations in FCGR data in a given test can primarily be attributed to non-homogeneous structure of the weld metal, where the crack path and crack front are more erratic than in wrought metals, and to the presence of some level of residual stress from welding.

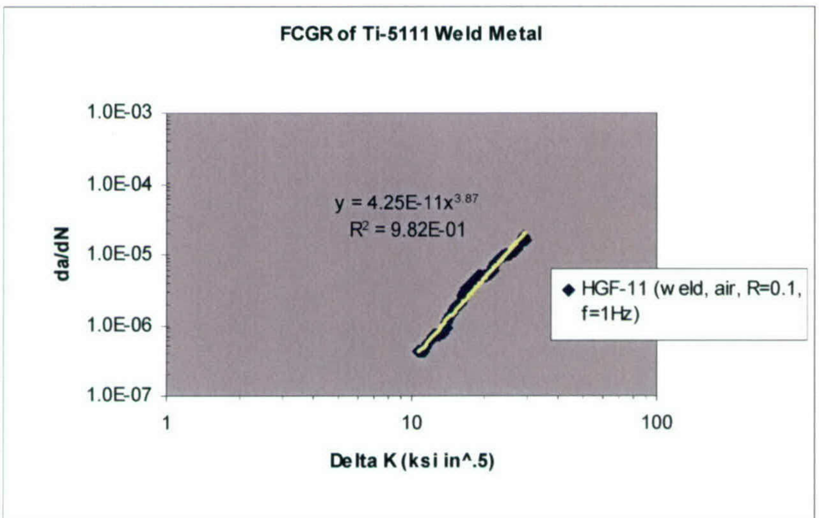

Figure 4: Fatigue Crack Growth Rates for Ti-5111 Weld Metal in Air

A linear region of crack growth of the weld metal in air ranging from ΔK = 10 ksi√in to approximately ΔK = 40 ksi√in is shown in Figure 4. These data are compared to fatigue crack growth rates of Ti-5111 weld metal in aerated seawater in Figure 5. The FCGR behavior in seawater exhibited slightly higher crack growth rates than the weld metal tested in air. However, Figure 6 shows that the applied cathodic potential of -0.987 V minimized the effect of seawater on specimen HGF-13; however, the cathodic potential did not have a significant effect on specimen HGC-7a. Additional research is required to fully understand the effect of applying a cathodic potential to Ti-5111 fatigue crack growth rate specimens.

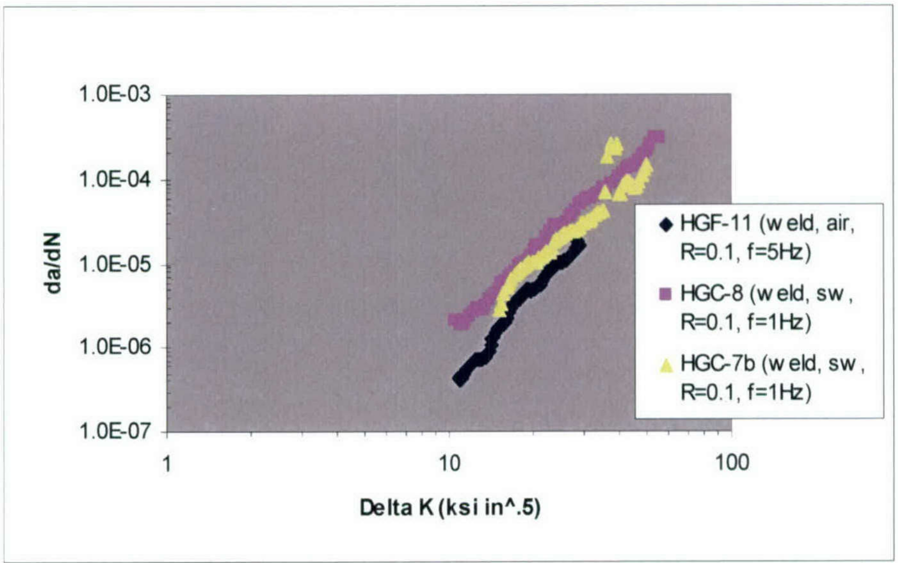

Figure 5: Fatigue Crack Growth Rates in Ti-5111 Weld Metal in Seawater (sw) and in Air

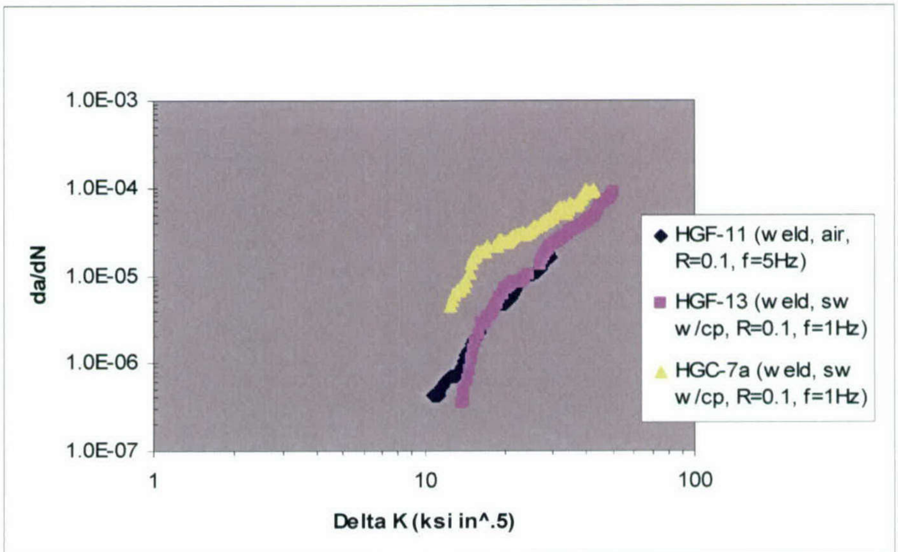

Figure 6: Effect of Seawater With Applied Cathodic Potential on Fatigue Crack Growth Rates in Ti-5111 Weld Metal

Figure 7 compares the similar FCGR behavior in air of Ti-5111 weld metal and Ti-5111 plate tested in air in other studies [2,5]. The graph indicates slightly lower fatigue crack growth rates through the weld metal, which may be attributed to the more tortuous crack path in the weld metal and to the presence of residual stress from welding.

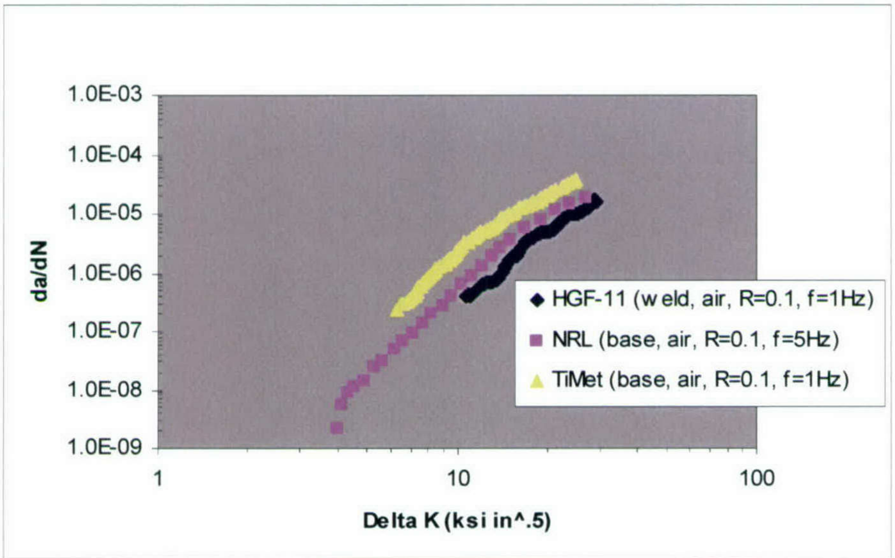

Figure 7: Comparison of Fatigue Crack Growth Rates in Air in Ti-5111 Plate and Ti-5111 Weld Metal

Similarly, FCGR data from Ti-5111 weld metal specimens HGC-8 and HGF-7B, conducted in seawater, are plotted in Figure 8 compared to FCGR data for Ti-5111 plate [2,5] conducted in seawater environment. The FCGR behavior of Ti-5111 plate and weld metal were similar.

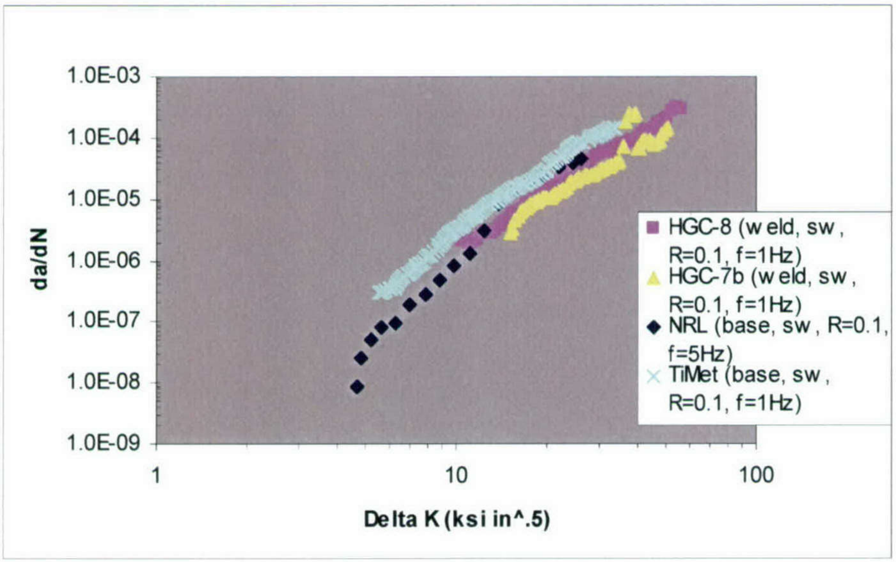

Figure 8: Comparison of Fatigue Crack Growth Rate Behavior of Ti-5111 Plate and Weld Metal in Seawater

For supplemental documentation of FCGR data for Ti-5111, results for Ti-5111 plate developed by NRL [5] in air and seawater at two different load ratios, R = 0.1 and R = 0.9, are shown in Figure 9. The high load range represents fatigue crack growth under conditions of a high, steady crack-opening load with a low amplitude ripple loading. Such conditions have been shown to degrade the stress corrosion cracking resistance in saltwater of otherwise SCC resistant high strength titanium alloys [8]. As shown in Figure 9, there was no significant effect of the seawater environment on FCGR at the high load ratio. Also, it should be noted that the testing frequency of the specimens in seawater (f = 5 Hz) was the same as those specimens tested in air, and is relatively high for a corrosion FCGR test.

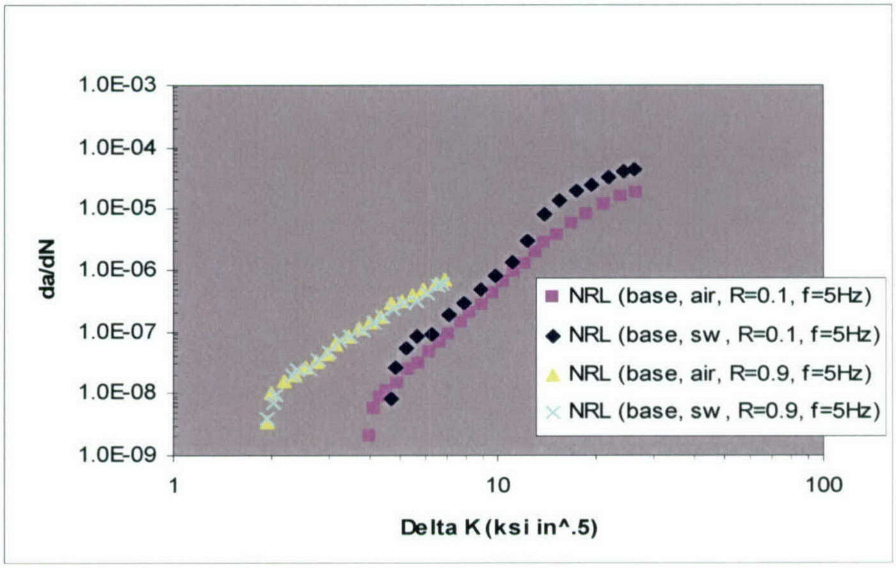

Figure 9: Fatigue Crack Growth Rate Behavior in Ti-5111 Plate in Air and Seawater at Low and High Load Ratios (NRL [5])

Because the Ti-5111 system was developed as an alternative to Ti-100 in naval applications, a comparison of FCGR behavior of Ti-5111 to Ti-100 is relevant. Fatigue crack growth rate results for Ti-5111 plate [2,5] are compared to results for Ti-100 plate [6] in Figure 10. The results show that Ti-100 and T-5111 plate tested in air exhibit similar fatigue crack growth rates where data were available in overlapping stress intensity ranges. Figure 11 compares FCGR behavior of Ti-5111 and Ti-100 plate in seawater, in addition to Ti-5111 weld metal in seawater. The results indicate little significant difference among the fatigue crack growth rate curves for Ti-100 plate, Ti-5111 plate, and Ti-5111 weld metal in a seawater environment.

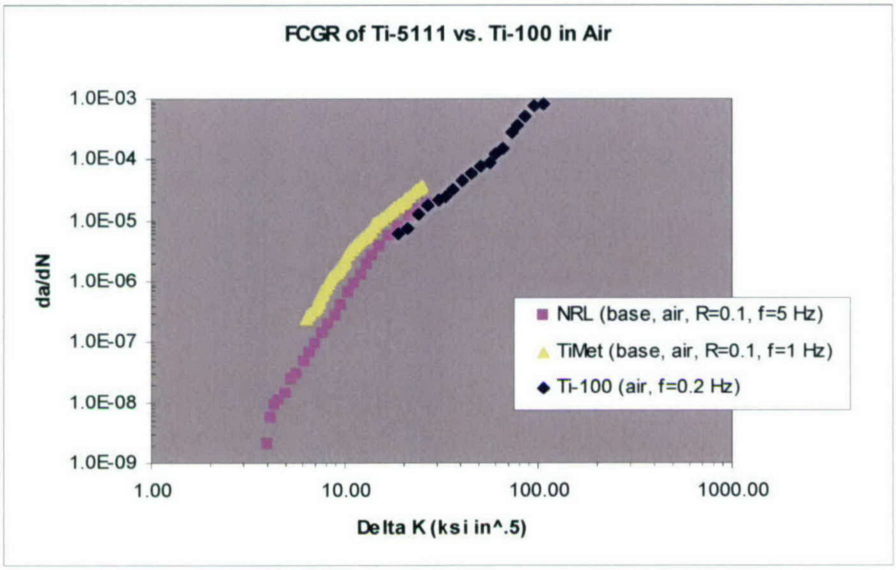

Figure 10: Comparison of Fatigue Crack Growth Rate Behavior in Ti-5111 Plate and Ti-100 Plate in Air

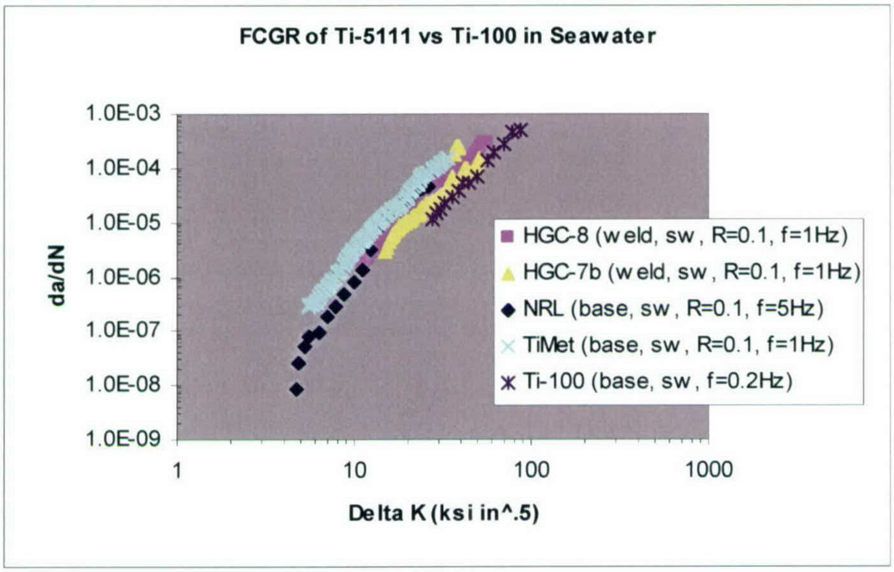

Figure 11: Comparison of Fatigue Crack Growth Rate Behavior in Ti-5111 Plate, Ti-100 Plate, and Ti-5111 Weld Metal in Seawater

CONCLUSIONS

Fatigue crack growth rates in Ti-5111 weld metal were obtained in both air and artificial seawater environments. The results indicated that there was only a minor effect of the seawater environment on the FCGR behavior of Ti-5111 weld metal. Applied cathodic potential equivalent to that applied by zinc anodes provided mixed results. One specimen demonstrated fatigue crack growth rates in seawater similar to those in air, while increased crack growth rates were observed in a second specimen. Further testing would be required to fully understand the effect of cathodic potential on the fatigue crack growth rates of Ti-5111 in artificial seawater.

Ti-5111 weld metal FCGR data was compared to FCGR data for Ti-5111 and Ti-100 plate product, and the following was concluded:

- Ti-5111 plate and weld metal showed similar behavior, with FCGR in the Ti-5111 weld metal having slightly lower fatigue crack growth rates than Ti-5111 plate in air.
- in all comparisons, Ti-5111 plate and weld metal exhibited similar fatigue crack growth rates to Ti-100 plate.

REFERENCES

1. Bania, P. J., P. G. Allen, and W. M. Parris, "Development of a Near-Alpha Alloy with Excellent Energy Related Toughness," *Proceedings, Eighth World Conf. On Titanium*, Birmingham, England, October 1995.

2. Been, J., "Titanium Alloy 5111 Brings Intermediate Strength, Excellent Toughness, and Corrosion Resistance to Naval Operating Environments," Paper No. 499, *Corrosion '99*, NACE International, Houston TX (1999).

3. Been, J., D. Davis, and D. Aylor, "Corrosion Property Evaluation of Ti 5111 in Marine Environments," Paper No. 00641, *Corrosion 2000*, NACE International, Houston TX (2000).

4. Czyryca, E. J., M. E. Wells, and K. Tran, "Titanium Alloy Ti-5111 for Naval Applications," *Proceedings, Advanced Marine Materials: Technology & Applications*, The Royal Institution of Naval Architects, London, UK (2003), pp. 41 – 49.

5. Pao, P., "Ti-5111 SCC and Corrosion Fatigue Properties," NRL Memorandum Code 6132, 18 Mar 1999.

6. Cares, W. R. and T. W. Crooker, "Fatigue Crack Growth of Ti-6Al-2Cb-1Ta-0.8Mo Alloy in Air and Natural Sea Water Environments," NRL Memorandum Report 2617 (June 1973).

7. Dowling, N., *Mechanical Behavior of Materials*, 2nd Edition, Prentice Hall, Inc. (1999), pp. 488 – 558.

8. Pao, P. S., R. A. Bayles, S. J. Gill, D. A. Meyn, and G. R. Yoder, "Ripple Load Degradation in Titanium Alloys," *Proceedings, Titanium '92, Science and Technology*, The Minerals, Metals, & Materials Society (1993), pp. 2169 – 2176.

This page intentionally left blank

Distribution

	Copies
DoD-CONUS	
CHIEF OF NAVAL RESEARCH ATTN ONR 332 (J. CHRISTODOULOU) BALLSTON CENTRE TOWER ONE 800 NORTH QUINCY ST ARLINGTON VA 22217-5660	1
COMMANDER ATTN SEA 05M NAVAL SEA SYSTEMS COMMAND 1333 ISAAC HULL AVE SE STOP 5130 WASHINGTON NAVY YARD DC 20376-5130	1
COMMANDER ATTN SEA 05M1 (D. THOMAS) NAVAL SEA SYSTEMS COMMAND 1333 ISAAC HULL AVE SE STOP 5131 WASHINGTON NAVY YARD DC 20376-5131	1
COMMANDER ATTN SEA 05M2 (G. MITCHELL) NAVAL SEA SYSTEMS COMMAND 1333 ISAAC HULL AVE SE STOP 5132 WASHINGTON NAVY YARD DC 20376-5132	1
COMMANDER ATTN SEA 05P1 NAVAL SEA SYSTEMS COMMAND 1333 ISAAC HULL AVE SE STOP 5141 WASHINGTON NAVY YARD DC 20376-5141	1
COMMANDER ATTN SEA 05P2 NAVAL SEA SYSTEMS COMMAND 1333 ISAAC HULL AVE SE STOP 5142 WASHINGTON NAVY YARD DC 20376-5142	1
COMMANDER ATTN SEA 05P2 (J. A. MANUEL) NAVAL SEA SYSTEMS COMMAND 1333 ISAAC HULL AVE SE STOP 5142 WASHINGTON NAVY YARD DC 20376-5142	1
COMMANDER ATTN SEA 05P3 NAVAL SEA SYSTEMS COMMAND 1333 ISAAC HULL AVE SE STOP 5143 WASHINGTON NAVY YARD DC 20376-5143	1
COMMANDER ATTN SEA PMS 395 (R. KELTIE) NAVAL SEA SYSTEMS COMMAND 1339 PATTERSON AVE SE STOP 8840 WASHINGTON NAVY YARD DC 20376-8840	1

	Copies
COMMANDER ATTN SEA 08S NAVAL SEA SYSTEMS COMMAND 1240 ISAAC HULL AVE SE STOP 8034 WASHINGTON NAVY YARD DC 20376-8034	1
PROGRAM EXECUTIVE OFFICE ATTN PMS403 LITTORAL & MINE WARFARE - UUV 614 SICARD ST SE STOP 7014 WASHINGTON NAVY YARD DC 20376-7014	1
UNITED STATES NAVAL ACADEMY MECHANICAL ENGINEERING DEPT ATTN DR S M GRAHAM 590 HOLLOWAY RD ANNAPOLIS MD 21402-5042	1
UNITED STATES NAVAL ACADEMY MECHANICAL ENGINEERING DEPT ATTN DR R E LINK 590 HOLLOWAY RD ANNAPOLIS MD 21402-5042	1
NAVAL RESEARCH LABORATORY ATTN CODE 6320 4555 OVERLOOK AVE SW WASHINGTON DC 20375-5320	3
COMMANDER ATTN CODE 4121 (K. BEHAN) NAVAL UNDERSEA WARFARE CENTER NEWPORT DIVISION 1176 HOWELL ST NEWPORT RI 02841-1708	2
COMMANDER ATTN CODE 4122 (W. BARKER) NAVAL UNDERSEA WARFARE CENTER NEWPORT DIVISION 1176 HOWELL ST NEWPORT RI 02841-1708	2
COMMANDER ATTN CODE 3496 (T. MCELROY) NAVAL UNDERSEA WARFARE CENTER NEWPORT DIVISION 1176 HOWELL ST NEWPORT RI 02841-1708	2
DEFENSE TECHNICAL INFORMATION CENTER 8725 JOHN KINGMAN ROAD SUITE 0944 FORT BELVOIR VA 22060-6218	1

INTERNAL DISTRIBUTION

60		1
61		1
612		1
613		1
613	(AYLOR)	1
614		2
614	(CZYRYCA)	5
614	(FOCHT)	1
614	(J. GAIES)	1
614	(HAYDEN)	1
614	(IORIO)	1
614	(L'HEUREUX)	1
614	(MOUSSOUROS)	1
614	(PURTSCHER)	1
614	(ROE)	1
614	(STAUFFER)	5
614	(STILES)	1
614	(ZHANG)	1
615		1
615	(WELLS)	1
615	(TRAN)	1
62		1
63		1
64		1
65		1
651		1
652		1
653		1
654		1
3442	(TIC)	1

NAVSEA
WARFARE CENTERS
CARDEROCK